Security Lab – Cryptography in Java

Virtual Machine

This lab can be done with the **Ubuntu VM**. The remainder of this document assumes you are working with this VM.

You can do this lab also on your own system, provided you have an IDE and a current version of Java installed.

1 Introduction

When developing software, there's often the requirement to perform cryptographic operations. For instance, this may be the case in a program that encrypts and decrypts data or in a server application that uses the HTTPS protocol (HTTP over TLS). In these situations, it's not reasonable to completely implement ciphers or secure communication protocols on your own. Instead, you should use available, well-established components and focus on using them in a secure way.

This is exactly what you'll do in this lab. Your task is to use the cryptographic functions offered by Java to implement a program that can be used to encrypt and authenticate/integrity-protect files. The goal is that you get familiar with the cryptographic functions of Java and that you can apply them correctly.

You should first read the entire section 2 to deepen your knowledge about the Java Cryptography Architecture. With this information, you should then be ready to solve the task in section 3.

2 Basics: Java Cryptography Architecture

The Java Cryptography Architecture[1] (JCA) is a component of Java SE that provides various cryptographic functions including secret key block and stream ciphers, public key ciphers, key generators, hash functions, message authentication codes (MAC), digital signatures, and certificates. Other security components of Java are often based on the JCA, e.g., JSSE (for SSL/TLS) and JGSS (for Kerberos), but in this lab the focus is on the JCA.

2.1 Cryptographic Service Providers

The JCA uses a provider-based architecture, which means the actual implementations of the cryptographic functions are provided (in a plug-in manner) by software components identified as Cryptographic Service Providers[2] (CSP). Java SE includes several such CSPs[3] per default and as a result of this, Java SE supports virtually all of the widely used cryptographic functions «out of the box». The names of the integrated CSPs are – depending on the cryptographic function – for instance *SUN* (e.g., for random number generators), *SunJCE* (for several encryption algorithms), and others. In addition, there exist some CSPs that are provided by 3rd parties. If you want to use such a 3rd party CSP, you have to install it manually (see section 3). Usually, 3rd party CSPs are only used if Java SE does not support a specific cryptographic algorithm you want use. One of the most popular 3rd party CSPs is the Bouncy Castle CSP.

2.2 Basic Usage

To use a cryptographic function in a program, it is usually required to use the static method *getInstance* of the corresponding factory class of the JCA. For instance, to get an object to compute SHA256 hashes (based on SHA-2), this is done as follows:

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[1] https://docs.oracle.com/en/java/javase/17/security/java-cryptography-architecture-jca-reference-guide.html

[2] Basically, a CSP is a software component (i.e., a library) that can be plugged into the JCA and that contains classes that provide the functionality of one or more cryptographic algorithms.

[3] https://docs.oracle.com/en/java/javase/17/security/oracle-providers.html

```
MessageDigest md = MessageDigest.getInstance("SHA256");
```

The method returns a *MessageDigest* object from one of the installed CSPs – assuming at least one of them supports SHA-2 – and this object can then be used to compute SHA256 hashes. If multiple installed CSPs support the function, then the one with the highest priority is used.

When using the *getInstance* method of any of the factory classes of the JCA (e.g., *MessageDigest*, *Cipher*, *Mac*, *KeyGenerator* etc., details see below), then the returned object is typically from one of the CSPs that are included in Java SE per default, as they support a wide range of cryptographic operations. However, it may be that you need a cryptographic algorithm (e.g., an only recently published secret key cipher) that is not supported by the CSPs included in Java SE. In this case, as already mentioned above, you have to install a 3rd party CSP that supports the desired algorithm (e.g., the Bouncy Castle CSP). Once this has been done, the *getInstance* method can be used in the same way as above and will return an object from the 3rd party CSP.

If you want to explicitly specify the CSP to be used for a specific cryptographic operation, you can use a second variant of the method *getInstance*. So assuming that the Bouncy Castle CSP is installed and that you want to specifically use the SHA-2 implementation provided by this CSP (and not the one which is part of Java SE), this would be done as follows:

```
MessageDigest md = MessageDigest.getInstance("SHA256", "BC");
```

2.3 Classes

In the following, several classes of the JCA are described in detail, in particular also the ones that you need to use to successfully complete this lab. Additional information can be found in the Java API Specifications[4].

2.3.1 SecureRandom class

SecureRandom generates cryptographically strong random numbers. Java supports several random number generator (RNG) algorithms, depending on the underlying operating system. If possible, *SecureRandom* uses the random sources provided by the underlying operating system, e.g., */dev/random* or */dev/urandom* on Linux/Unix/macOS-like systems. These random sources either use a hardware random number generator (also called true RNG (TRNG)) if available on the system or a pseudo random number generator (PNRG) that is seeded with random material collected by the operating system (inputs from mouse, network, keyboard,...). In addition, *SecureRandom* also supports general PRNGs such as DRGB and SHA1PNRG, which are seeded by the random sources provided by the OS. In general, it's best to create *SecureRandom* objects without specifying the specific algorithm to use as this uses «the best» RNG (TRNG or PRNG) depending on the operating system. This is done as follows:

```
SecureRandom random = new SecureRandom();
```

If you really want to use a specific RNG, e.g., *SHA1PRNG*, the *SecureRandom* object is created as follows (but as mentioned above, you usually shouldn't do this):

```
SecureRandom random = SecureRandom.getInstance ("SHA1PRNG");
```

Random numbers are generated using the method *nextBytes()*. The following two lines generate 32 random bytes and store them in the array *bytes*:

```
byte bytes[] = new byte[32];
random.nextBytes(bytes);
```

[4] https://docs.oracle.com/en/java/javase/17/docs/api/index.html

2.3.2 Cipher class

A *Cipher* is used to encrypt data with an arbitrary algorithm. *Cipher* supports different symmetric and asymmetric algorithms and different padding schemes. The combinations that are supported by the providers that are included in Java per default are described online[5]. These combinations are named transformations and have the following form:

```
Algorithm/Mode/Padding
```

For instance, the following must be used for an AES cipher in CBC mode und PKCS5 padding (the method how the plaintext is increased to a multiple of the block length:

```
Cipher c1 = Cipher.getInstance("AES/CBC/PKCS5Padding");
```

Alternatively, one can also specify the algorithm name only. In that case, default values – depending on the used cipher – are used for mode and padding (in the case of AES, the default values are *ECB* (which is insecure!) and *PKCS5Padding*):

```
Cipher c2 = Cipher.getInstance("AES");
```

A *Cipher* can be used for different operations. Most relevant are *ENCRYPT_MODE* and *DECRYPT_MODE*. To use a *Cipher*, it must first be initialized using *init()*. The mode and a key (or a certificate in the case of asymmetric encryption) must be specified as parameters. Details about the key parameter (*key*) follow in section 2.3.4.

```
c1.init(Cipher.ENCRYPT_MODE, key);
```

In many cases (e.g., when using CBC, CTR or GCM mode or when using the cipher CHACHA20), an additional parameter must be specified to initialize the cipher (e.g., an initialization vector (IV)). This can be done by using a third parameter when initializing the cipher, which is an object of any of the JCA classes that provide parameter specifications (e.g., *IvParameterSpec*, *GCMParameterSpec*, *ChaCha20ParameterSpec* etc.) In this case, initialization of the cipher works as follows:

```
c1.init(Cipher.ENCRYPT_MODE, key, paramSpec);
```

Details about using this third parameter follow below in sections 2.3.5 - 2.3.7.

After having initialized the *Cipher* object, it can be used to directly encrypt or decrypt data (stored in a byte array) using *doFinal*. For instance, the following line encrypts the entire byte array *message1* and stores the ciphertext in *ciphertext*:

```
byte[] ciphertext = c1.doFinal(message1);
```

In the case of a block cipher, this includes correct padding of the final plaintext block.

Alternatively, it is also possible to encrypt step-by-step by calling the method *update* repeatedly. With a block cipher, only complete blocks are encrypted, the rest remains «within the *Cipher* object» and is processed during the next call of *update*. With a stream cipher, all bytes are usually processed. In general, the final operation must always be a call to *doFinal* (with or without additional data as parameter), as only this guarantees that the final block is padded correctly. With stream ciphers, the final call of *doFinal* is usually not «strictly» required as no padding is done, but it should still be done due to best practice as it is not guaranteed that update processes all bytes that could be processed, e.g., because of optimization reasons. As an example, the following three lines show twice a call of the *update* method and a necessary final call of *doFinal*. Note that the content of the byte array *ciphertext*

[5] https://docs.oracle.com/en/java/javase/17/docs/specs/security/standard-names.html

will of course be overwritten with each call, so it's important to store the received ciphertext after each call, e.g., by writing (appending) it into a file or into a larger byte array.

```
byte[] ciphertext = c1.update(message2a);
ciphertext = c1.update(message2b);
ciphertext = c1.doFinal();
```

Decrypting basically works the same (the main difference is that the *init* method must use *Cipher.DECRYPT_MODE*) and in this case, *doFinal* removes the padding from the last plaintext block after decryption.

If only the first *n* bytes in a byte array should be passed to the *update* method, this can also be done:

```
c1.update(message2c, 0, n);
```

To encrypt or decrypt entire streams, there exist the decorator classes *CipherInputStream* and *CipherOutputStream*. Objects of these classes are constructed by using an existing *InputStream* or *OutputStream* object and an initialized *Cipher* object. Subsequent *read()* or *write()* operations result in encrypting or decrypting the data from or to the underlying stream on-the-fly. As an example, the following line constructs a *CipherInputStream* object:

```
CipherInputStream cis = new CipherInputStream(inputStream, c1);
```

2.3.3 Mac class

Using message authentication codes (MAC) works similar as using ciphers. After creating a *Mac* object, *init()* is used to initialize it with a key and *doFinal* can be used to compute a HMAC over the data:

```
Mac m = Mac.getInstance("HmacSHA512");
m.init(key);
byte[] hmac = m.doFinal(message);
```

Note that the HMAC algorithm is always used together with a hash algorithm – in this case SHA512 – which is why we specified *HmacSHA512*.

Additional information about the key parameter (*key*) follows in section 2.3.4.

The *Mac* class also offers the *update* method, but it works a bit differently than with the *Cipher* class. The *update* method serves to "put" data (byte arrays) into the *Mac* object, but does not compute parts of the MAC. When all data has been "put in", the MAC over all data is computed using *doFinal*:

```
while ( ... ) {
  m.update(data-to-be-included-in-mac-computation);
}
hmac = m.doFinal();
```

Here again, the following variant can be used to only pass the first *n* bytes to the *Mac* object:

```
m.update(data, 0, n);
```

In contrast to *Cipher* and also *MessageDigest* (creates a hash without using any key) there are no decorator classes to use *Mac* with streams.

2.3.4 Key, KeySpec and KeyGenerator classes

Keys are a somewhat complex topic in JCA. Basically, there are two fundamental interfaces, the *Key* interface and the *KeySpec* interface. Classes implementing the *Key* interface are usually just "containers for key material" while classes implementing the *KeySpec* interface offer additional functionality, for instance to convert keys from one encoding to another. When initializing objects with keys, then objects that implement the `Key` interface (or its subinterfaces) are used.

Often used *Key*s are for instance *SecretKey* for symmetric encryption, *PrivateKey* and *PublicKey* (und their subinterfaces) for asymmetric encryption and *PBEKey* for password-based encryption.

Classes the implement the *KeySpec* interface or subinterfaces of *KeySpec* include for instance *SecretKeySpec* for symmetric keys, *RSAPrivateKeySpec* and *RSAPublicKeySpec* for RSA keys, *DHPrivateKeySpec* and *DHPublicKeySpec* for Diffie-Hellman keys and so on. In addition, there are the classes *PKCS8EncodedKeySpec* and *X509EncodedKeySpec*, both subclasses of *EncodedKeySpec*, which serve to read encoded private and public keys.

To create new key material, the *KeyGenerator* class can be used. The following generates a 128-bit long AES key:

```
kg = KeyGenerator.getInstance("AES");
kg.init(128);
SecretKey key = kg.generateKey();
```

The created key object (*SecretKey*) can then be used in the *init* method of *Cipher* or *Mac* (see *key* parameter of the *init* method in sections 2.3.2 and 2.3.3).

If the key material is available as a byte array (e.g., the 16 bytes of an AES key), you can use the class *SecretKeySpec* (which implements the *KeySpec* and the *SecretKey* interfaces and therefore also the *Key* interface) to create a key object. In the case of AES, this works as follows (*keyData* is a byte array that contains the key):

```
SecretKeySpec sKeySpec1 = new SecretKeySpec(keyData, "AES");
```

Likewise, it is possible to generate a key for a MAC; this simply requires specifying e.g., *HmacSHA256* instead of *AES*:

```
SecretKeySpec sKeySpec2 = new SecretKeySpec(keyData, "HmacSHA256");
```

Because the class *SecretKeySpec* implements the *SecretKey* interface (and therefore its superinterface *Key*), the generated key objects can also be used in the *init* method of *Cipher* or *Mac*.

To get the byte array representation from a key object (e.g., *SecretKeySpec* or *SecretKey*) you can use the *getEncoded* method:

```
byte[] keyBytes = key.getEncoded();
```

2.3.5 IvParameterSpec class

Many ciphers, e.g., when a block cipher is used in CBC mode, require an initialization vector (IV). If a cipher needs an IV and if no IV is specified when initializing the corresponding *Cipher* in *ENCRYPT_MODE*, *Cipher* generates its own IV. In *DECRYPT_MODE*, the IV must be explicitly specified.

In this lab, you'll include the IV in the header of an encrypted file (see section 3.3). Therefore, it's reasonable to explicitly create the IV using *SecureRandom* and use it in the *init* method when initializing the *Cipher* for encryption. The following lines show how an *IvParameterSpec* object is created based on an IV value *iv* (a byte array) and how it is then used to initialize the *Cipher* in *ENCRYPT_MODE*:

```
IvParameterSpec ivParameterSpec = new IvParameterSpec(iv);
cipher.init(Cipher.ENCRYPT_MODE, key, ivParameterSpec);
```

2.3.6 Galois/Counter Mode

The Galois/Counter Mode (GCM) is a block cipher mode that was developed to combine encryption with authentication and integrity protection. It only needs one key as an input and uses this to encrypt the plaintext and to compute an Auth Tag for authentication and integrity protection (the Auth Tag basically corresponds to a MAC). In addition, it supports «additionally authenticated data», which is data that is (in addition to the plaintext) also integrity-protected by the Auth Tag but that is not encrypted. This is very convenient to provide integrity-protection also for, e.g., a file header or a packet header.

Just like, e.g., CBC mode, GCM mode requires an IV. In addition, it requires the length of the Auth Tag, which can vary. To pass these parameters during initialization of the cipher, a *GCMParameterSpec* object must be created and used, similar to *IvParameterSpec* above. The following creates such an object using an IV value *iv* (a byte array created using *SecureRandom*) and 128 for the length of the Auth Tag:

```
GCMParameterSpec gcmParameterSpec = new GCMParameterSpec(128, iv);
cipher.init(Cipher.ENCRYPT_MODE, key, gcmParameterSpec);
```

Adding additionally authenticated data (as byte array) to the cipher must be done with the *updateAAD* method (this must be done *before* the data to be encrypted is processed with *update* or *doFinal*):

```
cipher.updateAAD(additionally-authenticated-data);
```

2.3.7 CHACHA20 Cipher

CHACHA20 is a relatively novel stream cipher. CHACHA20 requires two initialization parameters: a 12-byte nonce and a counter. The nonce basically corresponds to an IV. To pass these parameters during initialization of the cipher, a *ChaCha20ParameterSpec* object must be created and used, similar to *IvParameterSpec* and *GCMParameterSpec* above. The following creates such an object, assuming *nonce* contains the 12-byte nonce (a byte array created using *SecureRandom*) and *counter* contains the counter:

```
ChaCha20ParameterSpec chaCha20ParameterSpec =
                      new ChaCha20ParameterSpec(nonce, counter);
cipher.init(Cipher.ENCRYPT_MODE, key, chaCha20ParameterSpec);
```

According to RFC 8439, *counter* is typically set to 1, which we will also do in this lab.

2.3.8 CertificateFactory and Certificate classes

CertificateFactory reads data in X.509 format and creates *Certificate*[6], *CertPath* or *CRL* objects from this data. This allows, e.g., to verify certificates or to use the public key stored in a certificate for encryption. The following lines read a certificate from an *InputStream* and create a corresponding *Certificate* object.

```
cf = CertificateFactory.getInstance("X.509");
Certificate certificate = cf.generateCertificate(
                          certificateInputStream);
```

This certificate can then be used, e.g., to initialize an RSA *Cipher*, which uses the public key in the certificate for encryption:

---

[6] Note that there are multiple *Certificate* classes in Java SE, here you have to use *java.security.cert.Certificate*.

```
Cipher cipher = Cipher.getInstance("RSA/ECB/OAEPPadding");
cipher.init(Cipher.ENCRYPT_MODE, certificate);
```

Make sure to use *RSA/ECB/OAEPPadding* for the algorithm parameter as this guarantees usage of a secure RSA padding scheme.

2.3.9 Signature class

Signature is used to create digital signatures. Creating a corresponding object and initializing it with a private key works as follows:

```
Signature signing = Signature.getInstance("SHA256withRSA")
signing.initSign(privateKey);
```

The specified algorithm is always a combination of a hash function and a public key algorithm, as data to sign are first hashed and the signature is created over the hash. The variable *privateKey* must be an object of the class *PrivateKey*, which contains the private key to sign (in this case, it must be an RSA private key). Assuming the private key is available as a byte array *privateKeyBytes* that contains a PKCS #8-encoded RSA private key, the corresponding *PrivateKey* object can be created as follows:

```
PKCS8EncodedKeySpec keySpec =
                    New PKCS8EncodedKeySpec(privateKeyBytes);
KeyFactory kf = KeyFactory.getInstance("RSA");
PrivateKey privateKey = kf.generatePrivate(keySpec);
```

Finally, data to sign can be fed into the *Signature* object and calling *sign* creates the signature:

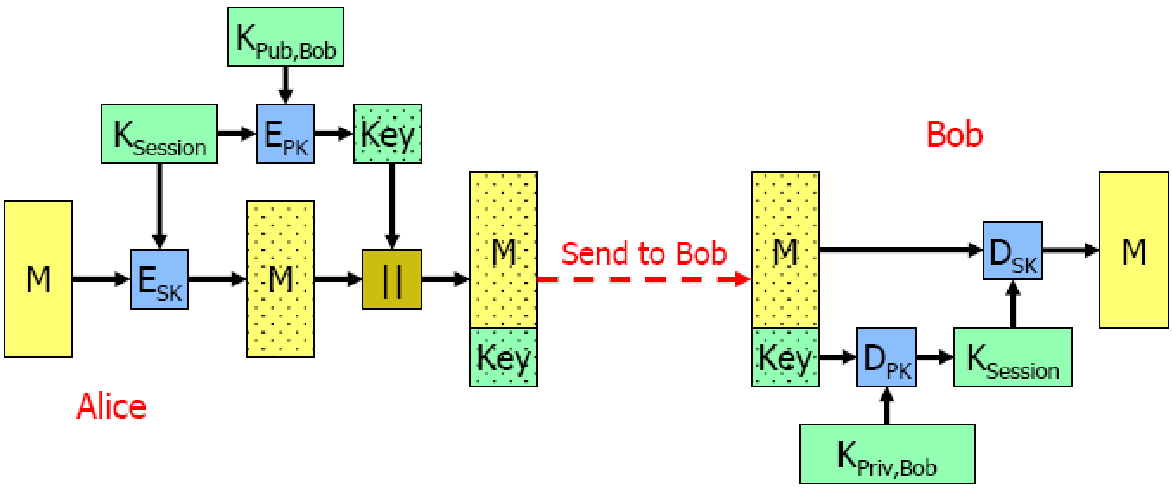
```
signing.update(dataToSign);
byte[] signature = signing.sign();
```

3 Task

This section describes the task you have to solve. Read through the entire section 3 (including all sub-sections) before you start implementing to understand correctly what you have to do.

Your task is to develop a program to encrypt and authenticate/integrity-protect arbitrary data using different cryptographic algorithms. The name of the program is SLCrypt (SL for Security Lab). You don’t have to develop the entire program from scratch as a significant portion of it (including the entire decryption part) is already provided as a basis.

To encrypt the data, hybrid encryption is used. The concept of hybrid encryption (and decryption) is illustrated in the following image, where Alice sends an encrypted message to Bob:



With hybrid encryption, the sender Alice first encrypts a message (M, this can be any data) with a secret key cipher using a randomly generated key ($K_{Session}$). This secret key is then encrypted with a public key cipher using the public key of the recipient Bob ($K_{Pub,Bob}$) and attached to the encrypted message. The encrypted message and the encrypted secret key are then sent to Bob, who first decrypts the secret key using his private key ($K_{Priv,Bob}$). Next, Bob uses the secret key to decrypt the message.

Because raw encryption without authentication and integrity protection is problematic (as it allows attacks against the authentication and integrity of the encrypted data), SLCrypt optionally supports using a message authentication code (MAC) or a signature. If used, then this MAC/signature is computed and appended when encrypting the data and checked for correctness when decrypting the data. If a MAC is used, a password is used as MAC key. If a signature is used, a private key and corresponding certificate is used.

Furthermore, SLCrypt also supports encryption with the Galois/Counter Mode (GCM). In this mode, authentication/integrity-protection is «already included» as described in section 2.3.6. However, SLCrypt still supports using an additional MAC or signature also with this cipher mode for security reasons. The reason is, as you will see, that SLCrypt without using a MAC or a signature won't provide authentication if GCM is used, because the key-exchange itself (as illustrated in the hybrid encryption scheme above) is not authenticated. As a result of this, using CGM without additional authentication/integrity-protection is not really more secure than other cipher modes (that provide encryption only) because an attacker could easily create and send a message while claiming to be somebody else (which violates authentication), and he could easily intercept a message and simply replace it with any valid message of his own choice (which violates integrity). Therefore, in SLCrypt, even if GCM is used, it should always be combined with a MAC or a signature.

To completely solve this lab, your program must support the following ciphers (if necessary, consult module IT-Sicherheit, where most of these ciphers, all modes, and *PKCS5Padding* are explained):

- *AES/CBC/PKCS5Padding* with key lengths 128, 192, and 256 bits. AES uses an IV of 16 bytes in all modes (except ECB mode, which is not considered here).
- *AES/GCM/NoPadding* with key lengths 128, 192, and 256 bits. GCM uses an Auth Tag, for which a length of 128 bits is used in this lab.
- *AES/CTR/NoPadding* with key lengths 128, 192, and 256 bits. This means AES in counter mode, which is a mode to use a block cipher as the keystream generator for a stream cipher.
- *SEED/CBC/PKCS5Padding*, *SEED/GCM/NoPadding* and *SEED/CTR/NoPadding*, which use the SEED block cipher. SEED uses a key length of 128 bits and the IV has a length of 16 bytes.
- *RC4* with a key length of 128 bits. Note that RC4 is no longer considered to be secure, but it's still included here as an example of a stream cipher that does not use an IV.
- *CHACHA20*, which is a stream cipher with a key length of 256 bytes. CHACHA20 uses two initialization parameters: a 12-byte nonce (which basically corresponds to an IV) and a counter (for which the value 1 is used in this lab).

In addition, your program must support the following MAC algorithms:

- *HmacSHA1*
- *HmacSHA256* (based on SHA-2)
- *HmacSHA512* (based on SHA-2)
- *HmacSHA3*-256 (based on SHA-3)
- *HmacSHA3*-512 (based on SHA-3)

And finally, your program must support the following signature algorithms:

- *SHA1withRSA*

- *SHA256withRSA* (based on SHA-2)
- *SHA512withRSA* (based on SHA-2)
- *SHA3-256withRSA* (based on SHA-3)
- *SHA3-512withRSA* (based on SHA-3)

Note that the Java version available on the Ubuntu image (Java SE 17) does not support the SEED cipher. Therefore, you must additionally use the 3rd party Bouncy Castle CSP, which provides the SEED cipher. To do this, do the following:

- Download the latest version of the Bouncy Castle CSP library from *https://www.bouncycastle.org/latest_releases.html*. The name of the file is *bcprov-jdk18on-xyz.jar*, e.g., *bcprov-jdk18on-175.jar*.
- Open */usr/lib/jvm/java-17-openjdk-amd64/conf/security/java.security* in an editor (as *root*) and add the Bouncy Castle CSP at the end of the listed CSPs, using «the next free» priority number (e.g., 13 in the example below):

  security.provider.11=JdkSASL
  security.provider.12=SunPKCS11
  security.provider.13=org.bouncycastle.jce.provider.BouncyCastleProvider
- When running the program (see section 3.2), include the CSP library in the classpath[7], e.g.:

```
java –cp bcprov-jdk18on-xyz.jar:. ...
```

- As a sidenote (you don't have to do this in this lab): A CSP can also be added programmatically instead of adding it to *java.security*. This can be done, in the case of the Bouncy Castle CSP, by using the line *java.security.Security.addProvider(new BouncyCastleProvider());* in the program, e.g., in the main method. But note that with this approach, the programmer determines the CSP to be used while in the case of using *java.security*, the owner (or administrator) of the system where the program is executed determines the CSP to be used (as you can use any CSP you want, it only has to provide an implementation of the SEED cipher). In practice, you have to decide which of the two approaches makes more sense depending on the specific needs. As another sidenote, one could of course also add the Bouncy Castle CSP as a dependency in *pom.xml* and configure *pom.xml* so that it creates a *jar* file that includes all dependencies. In that case, you wouldn't have to manually download the library and also wouldn't have to include it in the classpath. However, we decided against this option in this lab so you can see explicitly how libraries of CSPs are used.

3.1 Basis for this Lab

As mentioned above, a significant part of SLCrypt is already provided as a basis. Do the following to set up and use this basis:

- Download *SLCrypt.zip* from Moodle.
- Move the file to an appropriate location (e.g., into a directory *securitylabs* in the home directory */home/user*).
- Unzip the file. The resulting directory *SLCrypt* contains a Java project based on Maven. This should be importable in any modern IDE. The remainder assumes you are using *NetBeans*, which is installed on the Ubuntu image.
- Start *NetBeans* and open the project.
- To build the project, right-click *SLCrypt* in the *Projects* tab and select *Build*.

[7] On Windows systems, a semicolon (`;`) instead of a colon (`:`) must be used in the classpath.

  - Whenever you make changes and save them, the project should be automatically rebuilt. However, this does not work reliably and therefore, it's recommended that you always select *Build* again before running the program.
  - The executable code is placed in directory *SLCrypt/target/classes*.

- There's a directory *data* (just below *SLCrypt/target/classes*) that contains two certificates and corresponding private keys (*encryptCert.crt* and *encryptKey.key* will be used for encrypting and decrypting the secret key, and *signKey.key* and *signCert.crt* will be used for signing and verifying the signature). Also, the directory contains a test plaintext file (*testdoc.txt*) that can be used to test the program.

3.2 Program Usage

SLCrypt is a command line program. Run it in a terminal (not in the IDE) as user *user*. SLCrypt consists of two main components (each has its own *main* method): *SLEncrypt* for encryption and *SLDecrypt* for decryption. In the following, the usage of *SLEncrypt* is explained because your task is to complete the encryption component of SLCrypt. Usage of *SLDecrypt* will be explained in section 3.5.

SLEncrypt is used as follows (in directory *SLCrypt/target/classes* in a terminal):

```
$ java ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt plain_file
  encrypted_file certificate_file_for_encryption cipher_algorithm
  key_length auth_int_protection_type(M|S|N)
  [auth_int_protection_algorithm] [[mac_password] |
   [private_key_file_for_signing certificate_file_for_verification]]
```

The parameters have the following meaning:

- *plain_file* is the name (relative or absolute path) of the file that contains the plaintext document to be encrypted. Note that in the remainder of this lab, the term *document* is used to identify the actual data to be encrypted, i.e., the content of the file specified with this parameter. For this parameter, you can use the test file in *SLCrypt/target/classes/data* or any other file.

- *encrypted_file* is the file name (relative or absolute path) where the encrypted (and authenticated/integrity-protected) document should be stored. You can store it in *SLCrypt/target/classes/data* or in any other location.

- *certificate_file_for_encryption* is the file name of the X.509 certificate (that contains the public key) of the recipient of the encrypted document and is used to encrypt the secret key. You can use the certificate with name *encryptCert.crt* in *SLCrypt/target/classes/data*.

- *cipher_algorithm* is the name of the cipher to use, e.g., *AES/CBC/PKCS5Padding*.

- *key_length* is the length of the encryption key in bits, e.g., *128*.

- *auth_int_protection_type(M|S|N)* identifies the algorithm type to use for authentication/integrity-protection: *M*(AC), *S*(ignature) or *N*(one). As mentioned, *N* is supported but not a smart choice.

- *auth_int_protection_algorithm* is the name of the MAC or signature algorithm to use, e.g., *HmacSHA256* or *SHA3-256withRSA*. This parameter is only used if *auth_int_protection_type* is *M* or *S*.

- *mac_password* is the password used to compute the MAC, e.g., *supersecret*. This parameter is only used if *auth_int_protection_type* is *M*.

- *private_key_file_for_signing* is the file name of the private key of the sender of the encrypted document and is used to compute the signature. You can use the private key with name *signKey.key* in *SLCrypt/target/classes/data*. This parameter is only used if *auth_int_protection_type* is *S*.

- *certificate_file_for_verification* is the file name of the X.509 certificate (that contains the public key) of the sender of the encrypted document and is used by the recipient to verify the signature. This must be the certificate that corresponds to the private key specified in parameter *pri-*

vate_key_file_for_signing. You can use the certificate with name *signCert.crt* in *SLCrypt/target/classes/data*. This certificate is not needed to encrypt and authenticate/integrity-protect the document, but (as you'll see below), it is included as metadata in the file that contains the resulting encrypted and authenticated/integrity-protected document, so this certificate can be used when verifying the signature. This parameter is only used if *auth_int_protection_type* is *S*.

Below there are three valid usage examples that should clearly show how the program is used (they all use the files in directory *data* as described above and store the protected file in *data/textdoc.enc*):

- Encrypts the document in *data/textdoc.txt* with *AES/GCM/NoPadding* and a *128*-bit key and store the encrypted document in *data/testdoc.enc*. The certificate to encrypt the secret key is located in *data/encryptCert*. No authentication/integrity-protection is used (*auth_int_protection_type* is *N*):

```
$ java ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt
  data/testdoc.txt data/testdoc.enc data/encryptCert.crt
  AES/GCM/NoPadding 128 N
```

- Just like above, but this time *AES/CBC/PKCS5Padding* with a *192*-bit key is used for encryption and a MAC (*auth_int_protection_type* is *M*) using *HmacSHA256* is used for authentication/integrity-protection. The MAC password is *supersecret*:

```
$ java ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt
  data/testdoc.txt data/testdoc.enc data/encryptCert.crt
  AES/CBC/PKCS5Padding 192 M HmacSHA256 supersecret
```

- This time, encryption uses *CHACHA20* with a *256*-bit key and a signature (*auth_int_protection_-type* is *S*) using *SHA512withRSA* is used for authentication/integrity-protection. *data/signKey.key* contains the private key to create the signature and the corresponding certificate (which will be included as metadata so the recipient can verify the signature) is located in *data/signCert.crt*.

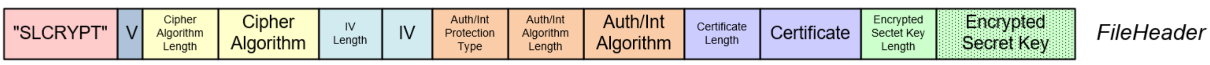
```
$ java ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt
  data/testdoc.txt data/testdoc.enc data/encryptCert.crt
  CHACHA20 256 S SHA512withRSA data/signKey.key data/signCert.crt
```

3.3 Cryptographic Operations and File Format

The protected files must follow a specific file format so the decryption part of SLCrypt (used, e.g., by the recipient of the protected file) can correctly decrypt and verify the protected files. Therefore, the file does not only contain the protected data, but also a file header with metadata. In the following, the process how a document is protected and the file format that is used for protected documents are described. We start with the plaintext document that must be protected.

To encrypt this document (this is described below), a secret key is created. To protect the secret key (remember that we are using hybrid encryption), the secret key is encrypted with the public key of the recipient. You get the public key from the certificate, which is passed to *SLEncrypt* on the command line (parameter *certificate_file_for_encryption*). This encryption uses RSA in PKCS #1 v2 format (use algorithm *RSA/ECB/OAEPPadding* to do this). The result is the data structure *EncryptedSecretKey*.

Next, the file header that contains metadata about algorithms and parameters used for document protection is created, which we identify as *FileHeader*.



The fields in the file header are as follows:

SLCRYPT	7 bytes	Identifier of the data format, is always *SLCRYPT*.
V(ersion)	1 byte	Version of the SLCrypt format. Here 1.
Cipher Algorithm Length	1 byte	Length of the cipher algorithm name (next field) in bytes.
Cipher Algorithm	> 0 bytes	The name of the cipher algorithm that is used. E.g., *AES/CBC/PKCS5PADDING*, *SEED/GCM/NoPadding*, *RC4, CHACHA20 etc*.
IV Length	1 byte	Length of the IV (next field) in bytes. 0 if no IV is used.
IV	≥ 0 bytes	The initialization vector that is used for encryption/decryption. If no IV is used (e.g., with RC4), the field is empty. In the case of CHACHA20, this field is used for the nonce.
Auth/Int Protection Type	1 byte	Type of the authentication/integrity-protection algorithm used. *M*(AC), *S*(ignature) or *N*(one).
Auth/Int Algorithm Length	1 byte	Length of the algorithm name for authentication/integrity-protection (next field) in bytes. 0 if none is used (i.e., if *Auth/Int Protection Type* is *N*).
Auth/Int Algorithm	≥ 0 bytes	The name of the algorithm for authentication/integrity-protection that is used. E.g., *HmacSHA1* or *HmacSHA512*. If no MAC is used (i.e., if *Auth/Int Protection Type* is *N*), the field is empty.
Certificate Length	2 bytes	Length of the certificate to verify the signature for authentication/integrity-protection (next fields) in bytes. 0 if none is used (i.e., if *Auth/Int Protection Type* is not *S*).
Certificate	≥ 0 bytes	Certificate to verify the signature for authentication/integrity-protection. If no signature is used (i.e., if *Auth/Int Protection Type* is not *S*), the field is empty.
Encrypted Secret Key Length	2 bytes	Length of the encrypted secret key (next field).
Encrypted Secret Key	> 0 bytes	The encrypted secret key (*EncryptedSecretKey*), corresponds to the secret key encrypted with RSA in PKCS #1 v2 format, using the public key from the certificate of the recipient.

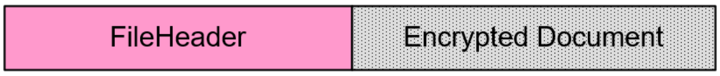
In the next step, the document is encrypted with the specified cipher algorithm using the secret key created before. Note that this is done differently depending on the cipher mode:

- With any mode other than GCM, the document is simply encrypted.
- With GCM, the document is also encrypted. But in addition, the file header is included as "additionally authenticated data". Note that in the case of SLCrypt, this does not really improve security due to the lack of an authenticated key-exchange if no MAC or signature is used (see discussion at beginning of Section 3). But in general, this is quite a valuable feature of the GCM mode, and therefore the file header is included as "additionally authenticated data" so you understand how this feature can be used in Java.

What results is what we identify as *EncryptedDocument*. Note that if we use GCM, this also includes the Auth Tag, but this is not specifically illustrated.

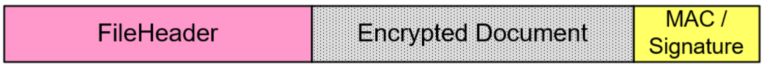
Encrypted Document	*EncryptedDocument*

Next, the header is prepended to the encrypted document. The resulting data structure is identified as *FileHeaderEncryptedDocument*:



FileHeaderEncryptedDocument

Finally, if a MAC or signature is used (i.e., if *Auth/Int Protection Type* is *M* or *S*), the MAC or the signature is computed over *FileHeaderEncryptedDocument* and appended to the data. This results in the final data structure, *FileHeaderEncryptedDocumentAuthInt*:



FileHeaderEncryptedDocumentAuthInt

If *Auth/Int Protection Type* is *N*, the step above is omitted and no MAC or signature is appended.

Note also that security-wise, this is a sound approach. In particular, we use the "Encrypt then MAC/sign" approach, which means data is first encrypted and only then authenticated and integrity-protected, which is more secure than "MAC/sign then Encrypt". For details, refer to module IT-Sicherheit.

3.4 Implementation

General program components are located in package *ch.zhaw.securitylab.slcrypt*. Classes that are specifically used for encryption can be found in package *ch.zhaw.securitylab.slcrypt.slencrypt* and those for decryption in package *ch.zhaw.securitylab.slcrypt.sldecrypt*. In the following, the classes that will be relevant for you are described.

ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt contains the *main* method to encrypt and authenticate/integrity-protect documents. The class checks the command line parameters, reads the plaintext document and the certificate with the public key from the file system, encrypts and authenticates/integrity-protects the document, and stores the protected document in the file system. For the actual encryption and authentication/integrity-protection, the method *encryptDocumentStream()* in the abstract class *ch.zhaw.securitlab.slcrypt.encrypt.HybridEncryption* is used. *encryptDocumentStream()* performs the complete encryption and authentication/integrity-protection of a document by calling six abstract methods in the same class. To complete the program, you have to implement these six methods in a subclass of *HybridEncryption*. For this, the class *HybridEncryptionImpl* is provided, which already contains skeletons of the methods. Do only work with *HybridEncryptionImpl*, don't change any other class.

Before we discuss the six methods, we look at two additional classes you will use, and which are already completely implemented:

- *ch.zhaw.securitylab.slcrypt.FileHeader* manages the data structure *FileHeader* (see above). It provides getter and setter methods to get and set the cipher algorithm, the IV, the authentication/integrity-protection type (*M*,*S*,*N*), the authentication/integrity-protection algorithm, the certificate to verify the signature, and the encrypted secret key (*getCipherAlgorithm()*, *setCipherAlgorithm()* etc.). The class also has a method *encode()*, which – after having set all attributes – returns the *FileHeader* data structure as a byte array. This class also offers decoding functionality, but this is only used during decryption, so you won't use it.
- *ch.zhaw.securitylab.slcrypt.Helpers* provides helper methods that will be useful. For instance, it provides methods *isCBC()*, *isGCM()* and *isCHACHA20()* that return whether a cipher algorithm uses CBC mode or GCM or whether the cipher is a CHACHA20 cipher. Likewise, *hasIV()* returns whether a cipher algorithm uses an IV (this method also returns true if CHACHA20 is used, as the nonce used by CHACHA20 is basically an IV). Furthermore, *getCipherName()* returns the raw cipher name of a cipher algorithm, e.g., it returns *AES* when *AES/CBC/PKCS5PADDING* is passed as parameter. Also, *getIVLength()* returns the length of the IV of a cipher algorithm in bytes.

In the following, the six methods you have to implement in *HybridEncryptionImpl* are described:

```
byte[] generateSecretKey(String cipherAlgorithm,
                         int keyLength)
```

generateSecretKey takes the cipher algorithm name (such as *AES/CBC/PKCS5Padding*) and the key length (in bits) as parameters and creates and returns a secret key that can be used for encryption as a byte array.

```
byte[] encryptSecretKey(byte[] secretKey,
                        InputStream certificateEncrypt)
```

encryptSecretKey takes the secret key and an input stream from which the certificate for encryption can be read as inputs. It uses the RSA public key in the certificate to encrypt the secret key. The encrypted secret key is returned as a byte array.

```
FileHeader generateFileHeader(String cipherAlgorithm,
                              char authIntType,
                              String authIntAlgorithm,
                              InputStream certificateVerify,
                              byte[] encryptedSecretKey)
```

generateFileHeader takes the cipher algorithm name, the authentication/integrity-protection type (*M*,*S*,*N*), the authentication/integrity-protection algorithm name, the certificate that contains the public key to verify the signature of the sender, and the encrypted secret key as inputs and returns a corresponding *FileHeader* object. To do this, the method first creates a *FileHeader* object and next, it sets the cipher algorithm name, the IV (which must first be created randomly, using the correct length), the authentication/integrity-protection type, the authentication/integrity-protection algorithm name, the certificate, and the encrypted secret key in the *FileHeader* object (using the setter methods provided by class *FileHeader*). If the cipher does not require an IV, the IV in the *FileHeader* object should be set to a byte array of length 0. If no authentication/integrity-protection is used, set the authentication/integrity-protection to the empty string. If no certificate is used, set the certificate to a byte array of length 0.

```
byte[] encryptDocument(InputStream document,
                       FileHeader fileHeader,
                       byte[] secretKey)
```

encryptDocument takes an input stream, from which the document to protect can be read, the pre-filled *FileHeader* object, and the secret key to use for encryption as inputs. It encrypts the document using the secret key and returns the encrypted document as byte array. In this method, you must distinguish between the different cipher algorithms (the one to use has been previously stored in the *FileHeader* object). For instance, if an IV (or a nonce) is required, use the IV that was previously filled into the *FileHeader* object. In addition, if GCM is used, make sure to add the file header (use *encode()* to get it as a byte array) as additionally authenticated data before encryption. Also, use 128 bits for the length of the Auth Tag if GCM is used. If CHACHA20 is used, use the value 1 for the counter. Furthermore, note that because the document is available as an input stream, it makes sense to use the class *CipherInputStream* (see section 2.3.2) to encrypt the document.

```
byte[] computeMAC(byte[] dataToProtect,
                  String macAlgorithm,
                  byte[] password)
```

computeMAC receives a byte array with the data to protect, the MAC algorithm name to use, and a MAC password as inputs and computes the MAC over *dataToProtect* (note that *dataToProtect* corresponds to the data structure *FileHeaderEncryptedDocument* described above). The MAC is returned as a byte array.

```
byte[] computeSignature(byte[] dataToProtect,
                        String signatureAlgorithm,
                        InputStream privateKeySign)
```

computeSignature receives a byte array with the data to protect, the signature algorithm name to use, and an input stream from which the PKCS #8-encoded RSA private key for signing can be read, and computes the signature over *dataToProtect* (note that *dataToProtect* corresponds to the data structure *FileHeaderEncryptedDocument* described above). The signature is returned as a byte array.

Note that method *encryptDocumentStream()* in the abstract class *ch.zhaw.securit-lab.slcrypt.encrypt.HybridEncryption* makes sure that the right method *computeMAC* or *computeSignature* is called depending on the authentication/integrity-protection type, so you don't have to deal with this. Also, if the authentication/integrity-protection type is N, neither of these two methods is called.

As a final remark, note that a few things are still missing to turn this into «a really secure program». First of all, there are no measures to detect replay attacks. I.e., if an attacker intercepts a message and simply replays it two weeks later, the recipient cannot really say whether the message is fresh. Including a timestamp in the file header could be one way to fix this. Furthermore, the two certificates that are used (one belonging to the recipient is used for encrypting the secret key, and the other belonging to the sender is used to verify the signature) are just self-signed. In reality, this could be solved by using trusted certification authorities that issue (sign) these certificates so that the sender knows it is truly using the certificate of the sender to encrypt the secret key and that the recipient can get the identity of the sender from the certificate that is included in a received protected file. Also, sender and recipient, if a MAC is used, would somehow have to agree on the shared password, which is also out of scope of the program. However, the goal of this lab is to learn to use the cryptographic functions of Java correctly and not to create a program with all bells and whistles, and therefore the current limitations are certainly acceptable.

3.5 Testing

To test the correctness of the encryption component you developed, the decryption component *ch.zhaw.securitylab.slcrypt.decrypt.SLDecrypt* is provided. It reads an encrypted file that was created with *SLEncrypt*, verifies (if available) its authentication/integrity, and decrypts it using the private key. Then, it stores the decrypted document as a new file. It is used as follows (in directory *SLCrypt/target/classes* in a terminal):

```
$ java ch.zhaw.securitylab.slcrypt.decrypt.SLDecrypt encrypted_file
  decrypted_file private_key_file_for_decryption [mac_password]
```

encrypted_file is the file name of the encrypted document to use and *decrypted_file* the file name where to store the decrypted document. *private_key_file_for encryption* is the file name of the private key to be used to decrypt the secret key (here you can use the private key *encryptKey.key* in *SLCrypt/target/classes/data*, which corresponds to certificate *encryptCert.crt* you used for encryption). If authentication/integrity-protection of the encrypted document uses a MAC, then you have to specify the *mac_password* so the MAC can be verified. If a signature or no authentication/integrity-protection is used, this parameter is omitted. Note that the certificate to verify the signature (if a signature is used) does not have to be provided as a parameter, as it is included in the FileHeader.

For instance, if a file is encrypted as follows (this corresponds to the second example at the end of Section 3.2),

```
$ java ch.zhaw.securitylab.slcrypt.encrypt.SLEncrypt data/testdoc.txt
  data/testdoc.enc data/encryptCert.crt AES/CBC/PKCS5Padding 192 M
  HmacSHA256 supersecret
```

then the corresponding decryption can be done as follows (the decrypted document will be stored in *data/testdoc.dec*):

```
$ java ch.zhaw.securitylab.slcrypt.decrypt.SLDecrypt data/testdoc.enc
  data/testdoc.dec data/encryptKey.key supersecret
```

When decryption is completed, *SLDecrypt* shows an output as illustrated below (this corresponds to the example above where a MAC is used). This allows you to easily check whether the document could successfully be decrypted and whether authentication/integrity verification was successful.

```
MAC algorithm:       HmacSHA256
MAC received:        354d05030a41423224ae8a624ec796d1d3e9acefdf0ca8f65ea2805f66681ac3
MAC computed:        354d05030a41423224ae8a624ec796d1d3e9acefdf0ca8f65ea2805f66681ac3
=> MAC successfully verified

Cipher algorithm:    AES/CBC/PKCS5Padding
Key length:          192
Key:                 0959879a981ec3c1fdb89f6b520c51fe3570f8cb2527fa29
IV:                  7c306a1a03ca333adeeea8d633ad28a7

Plaintext (74 bytes): The ultimate test document for the security lab "Cryptography
in Java"!!!
```

If you manage to encrypt files with all ciphers and authenticate/integrity-protect them with all MAC/signature algorithms listed at the beginning of section 3, and if all variants can be correctly decrypted with *SLDecrypt* (including correct verification of the authentication/integrity), you are ready to collect the lab points.

Lab Points

In this lab, you can get **4 Lab Points**. To get them, you have to do the following:

- Create an ASCII text file that is used as plaintext file, i.e., that contains the document to protect. You can choose any content you want, but there should be a connection to your names and your group number (an easy way to do this is to supplement the test file in *SLCrypt/target/classes/data* with your group number and the names).
- Encrypt and authenticate/integrity-protect the plaintext document with your program 5 times to produce 5 different protected files. You must use the following algorithms and key lengths to create the protected files:
  - For encryption, each of the following encryption algorithms must be used exactly once, in combination with the specified key length:
    - *AES/CBC/PKCS5Padding* with a key length of 192 bits
    - *AES/GCM/NoPadding* with a key length of 256 bits
    - *SEED/CTR/NoPadding* with a key length of 128 bits
    - *RC4* with a key length of 128 bits
    - *CHACHA20* with a key length of 256 bits
  - For authentication/integrity-protection, use the following:
    - One of the files should not get any separate authentication/integrity-protection at all.
    - Two of the files should be authenticated/integrity-protected with a MAC. One with a *HMAC* algorithm based on *SHA-2*, the other with *HMAC* based on *SHA-3*. For the

  MAC password, choose anything you want, but make sure to include the password in the e-mail (see below).
  - Two of the files should be authenticated/integrity-protected with a signature. One with *RSA* and a hash function based on *SHA-2*, the other with *RSA* and a hash function based on *SHA-3*.

- Send an e-mail to the instructor that contains the 5 protected files and the MAC password. If the files can all be correctly decrypted (including successful verification of the authentication/integrity), you get 4 points.
- In addition, you must include the source code of your implementation of *HybridEncryptionImpl.java* (non-encrypted) in the e-mail.
- Use *SecLab - Java Crypto - group X - name1 name2* as the e-mail subject, corresponding to your group number and the names of the group members.